Narrow Bipolar Events as Indicators of Thunderstorm Convective Strength

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Abstract

Narrow Bipolar Event (NBEs) are impulsive in-cloud lightning discharges that are commonly detected by both ground-based and satellite-based radio-frequency sensors. In this paper, NBE flash rates are shown to be statistically correlated to cloud-to-ground (CG) lightning flash rates as recorded by an array of electric-field-change sensors located in Florida. In addition, NBE source heights are found to generally increase with increasing NBE flash rates. The inference is that NBE flash rates and source heights are generally driven by the intensity/strength of the convective updraft in thunderstorms. As a consequence, NBEs represent a meteorologically important type of lightning and provide an excellent target of opportunity for future satellite-based very high frequency (VHF) global lightning monitors.

1. Introduction

Narrow Bipolar Events (NBEs) are the very low frequency (VLF) manifestations of impulsive (~< 20 μs duration) in-cloud (IC) lightning discharges that are commonly observed by both ground-based electric-field-change sensors [e.g., *Le Vine,* 1980; *Willet et al*., 1989; *Smith et al*., 1999] and ground and satellite-based very high frequency (VHF) receivers [e.g., *Holden et al*., 1995; *Thomas et al*., 2001; *Suszcynsky et al*., 2001; *Jacobson and Light*, 2003]. They produce the most intense form of radio-frequency radiation emitted by lightning, are spatially compact [*Smith et al*., 1999], optically weak [*Light and Jacobson,* 2001] and can occur as temporally isolated impulses or as initiators of more generic forms of IC lightning flashes [e.g., *Willet et al.,* *1989*; *Jacobson and Light,* 2003]. It has been suggested that NBEs may represent a type of fast K change [*Le Vine*, 1980] although it has been difficult to develop a model to account for their distinct bipolar electric-field-change profile and what appears to be a unique and as yet unidentified generation mechanism [*Willet et al*., 1989].

Over the last few years, there has been a growing need to understand the relationship between NBE occurrence and deep tropospheric convection. Extensive studies with the Fast On-Orbit Recording of Transient Events (FORTE) satellite [e.g., *Jacobson and Light*, 2003] and an experimental VHF receiver system currently in use aboard a Global Positioning System (GPS) satellite [*Suszcynsky et al.,* 2001] have demonstrated that NBEs account for the majority of VHF lightning detected from space and as such, provide the primary target of opportunity for future satellite-based VHF global lightning monitors. Since the basic premise of satellite-based global lightning monitoring is to detect lightning as proxy for mapping and quantifying global convective activity, an understanding of the detailed meteorological context within which NBE activity occurs, particularly as it relates to deep tropospheric convection, is essential. Currently, there is little known about the meteorology of NBEs. They have been observed to occur near and within regions of high radar reflectivity associated with the convective cores of thunderstorms [*Smith et al*., 1999; *Thomas et al*., 2001] and there is evidence that their effective radiated powers are related to the source height in the cloud [*Jacobson*, 2003]. However, a direct link that relates the dynamics of convective updraft to the production of NBEs has yet to be established.

Convective updraft is one of the primary drivers of thunderstorm electrification and is integral to the transport and geometric distribution of charge and to the degree of charge separation within the thundercloud. Consistent with this picture is the prediction that the electrical energy in a thunderstorm, most conveniently measured in terms of the total lightning (CG plus IC) flash rate, should scale as the fifth power of the cold cloud-top height (i.e., strength of convective updraft) [*Vonnegut*, 1963; *Williams*, 1985]. Recent ground and satellite-based measurements of total lightning flash rates versus cloud-top heights [e.g., see review in *Williams*, 1985; *Ushio et al*., 2002] are in general support of this proposed scaling. Although the large variances in each of these results precludes the use of such relationships as single-parameter predictors of thunderstorm convective strength, the findings do serve to establish a fundamental relationship between the strength of the convective process and the electrical vigor within storms.

In the spirit of the total flash rate studies described in *Williams* [1985] and *Ushio et al*. [2002], a correlation between NBE flash rates and thunderstorm convective strength is a necessary prerequisite for any successful future deployment of a VHF global lightning monitor. This paper establishes the basis for satellite-based global VHF lightning monitoring by demonstrating that NBE flash rates and NBE source heights are, like total lightning flash rates, statistically correlated to the strength of the convective updraft in storms.

2. Instrumentation and Techniques

The Los Alamos National Laboratory (LANL) Sferic Array (LASA) is located in Florida and consists of eight capacitively coupled electric-field-change sensors that detect perturbations to the vertical electric field [*Smith et al.*, 2002]. The array is sensitive to both CG and IC lightning activity and provides excellent ground-truthing for both the FORTE and GPS VHF receivers. LASA stations are located in Tampa (TA), Gainesville (GV), Boca Raton (BR), Kennedy Space Center (KS), Daytona (DA), Tallahassee (TE), Ft. Meyers (FM) and Orlando (OR) (Fig. 1).

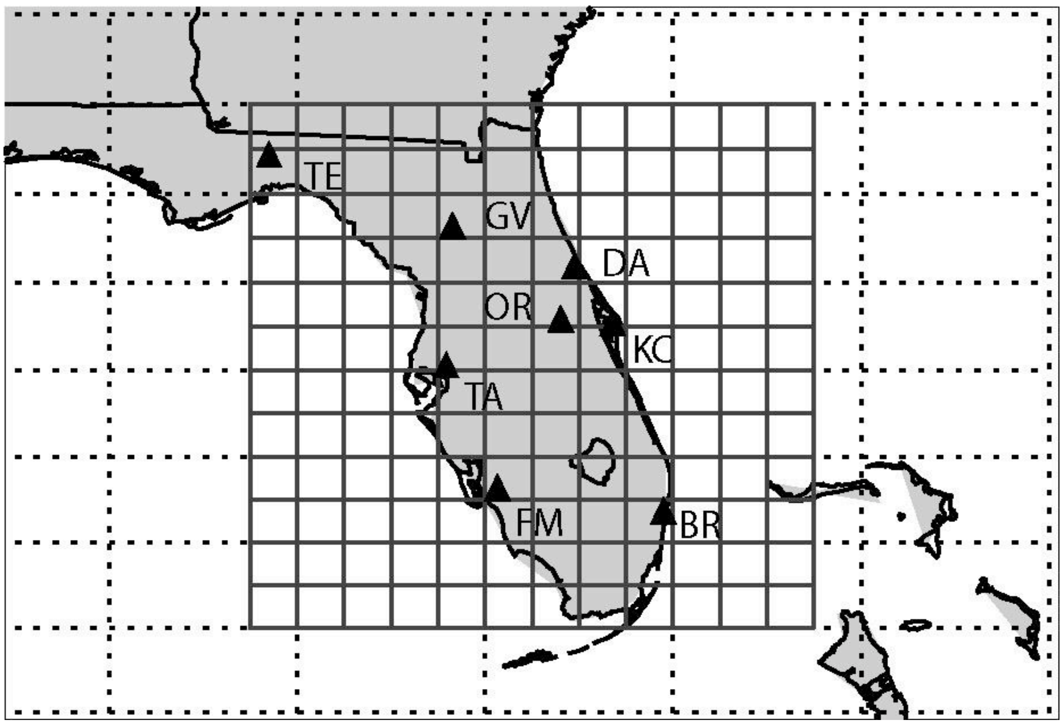

Figure 1. Map showing the locations of LASA stations and the geometry of the study grid.

When a lightning event occurs in the vicinity of the array, an 8.192-ms duration waveform is collected at a 1 MHz sampling rate at each station for which the local signal level exceeds a preset threshold amplitude. Once collected, the waveforms are GPS-time-stamped and then stored at their respective stations for later retrieval. Accumulated timestamps from each station are automatically transferred to LANL once per day where they are processed to identify temporal coincidences. If three or more stations are found to trigger on an event within a 20-ms time window, the full waveforms are sent to LANL via the Internet and two-dimensional event locations are determined by a time-difference-of-arrival technique [*Smith et al.,* 1999].

For the duration of this study, each array station was operated in the most sensitive mode possible given local background noise conditions (threshold ~ 0.25 V). In this mode of operation, detection efficiencies are maximized for events within 625 km of the center of the array and are estimated to be about 85% for CG lightning strokes [*Smith et al.*, 2000] and a few percent for generic IC lightning flashes. The detection efficiency for NBEs is unknown although we assume that the LASA-detected NBEs represent a significant and relatively unbiased sampling of the total NBE population. As a result of these efficiencies, the "LASA total lightning product" is comprised of about 93 % CG strokes and 7% IC triggers (two-thirds of these due to NBEs).

The study area for the analysis was a 6° by 6° grid centered on the LASA array stations and was chosen to lie well within the 625-km "high-detection-efficiency" range of the array (Fig. 1). The LASA total lightning flash rate, f_{TOT}, the LASA CG flash rate, f_{CG}, and the LASA NBE flash rate, f_{NBE}, were calculated for each of the 36 cells in the grid in 15-minute intervals for all of July and August, 2001 and 2002. Each grid cell is approximately 50 km by 50 km and was chosen to be small enough to isolate individual storm cells but large enough to ensure reasonable flash counts per 15-minute interval. A lightning flash was defined as a collection of LASA triggers within a single 15-minute space-time cell with no more than a 0.75-s time interval between any two successive triggers. A NBE flash was defined as a single NBE trigger since the time interval between successive LASA-detected NBEs is typically greater than conventional CG or IC flash timescales. Triggers were identified as NBEs by using an automated identification routine developed by *Smith et al.* [2002] that looks for waveform bipolarity, large signal-to-noise ratios (typically > 25 dB), rise-plus-fall times of less than about 7 μs, and temporal isolation from other electrical activity within the 8.192 ms record length. A justification for and more exact quantification of these selection criteria can be found in Fig. 14 of *Smith et al.* [2002]. Within the study area, 63 % of the LASA NBE detections were of positive polarity (waveform was initially positive-going) and 37 % were of negative polarity (waveform was initially negative-going).

The analysis in this study is based on the use of f_{CG} rather than f_{TOT} as a proxy for the strength of the associated convective activity since LASA is relatively insensitive to IC activity. Previous work has shown that, on the average, CG flash rates tend to scale according to convective strength in a manner similar to the total lightning flash rate. For example, *Holle and Maier* [1982] has shown that the maximum CG flash rates in storms are typically associated with cloud tops having the greatest vertical development. Additionally, *Price and Rind* [1993] have demonstrated that CG flash rates scale according to the cold cloud thickness (presumably related to the strength of the convective process). On the other hand, these statistical correlations typically have large variances and may even be contradicted during individual case studies (see review by *Williams* [2001]). However, given the statistical nature of this study, we conclude that f_{CG} should serve as a sufficient statistical indicator of convective strength.

3. Results and Discussion

3.1 NBE Flash Rates

Figure 2 plots the LASA CG flash rate, f_{CG}, versus the LASA NBE flash rate, f_{NBE}, for each of the 22,156 space-time cells in the study period that had both non-zero f_{CG} and f_{NBE} values (small dots). The data represent over 5,000 hours of lightning activity and suggest a correlation between f_{CG} and f_{NBE} with large variance. The flash rates are calculated from the number of flashes detected per 15-minute interval resulting in a noticeable quantization of the data at the lowest rates.

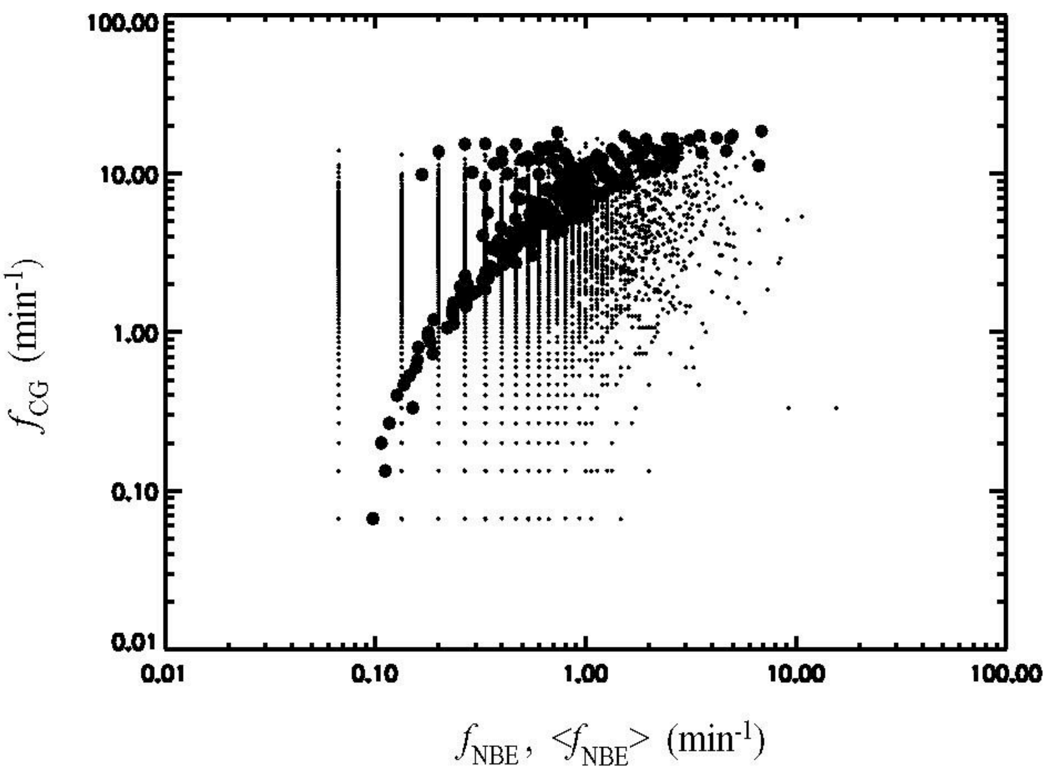

Figure 2. Plot of LASA CG flash rate, f_{CG}, versus NBE flash rate, f_{NBE}, for 22,156 space-time cells that had both non-zero CG and non-zero NBE flash rates (small dots) and the average NBE flash rate, $\langle f_{NBE}\rangle$, for all space-time cells of a given f_{CG} (large dots).

A more revealing representation of the data in Fig. 2 plots the average NBE flash rate, $< f_{NBE} >$, for all space-time cells of a given f_{CG} (large dots). This plot contains three distinct regions: a low-rate region (NBE rates less than ~ 0.15 min^{-1}), a mid-rate region (NBE rates from about 0.15 to 1 min^{-1}), and a high-rate region (NBE rates greater than 1 min^{-1}). The low-rate region is dominated by temporally isolated NBE flashes that occur at a rate of a few per 15-minute interval (weak lightning activity). The mid-rate region represents the most typical lightning activity levels and demonstrates a robust and statistically significant linear correlation between f_{CG} and f_{NBE}. The high-rate region shows a continued correlation between f_{CG} and f_{NBE} and a broadening and flattening of the data with increasing rates.

In the high-rate region, the broadening of the data is simply due to poor event statistics and the flattening of the data is due at least in part to a breakdown of the flash definition at these rates. In a high-rate regime, the flash definition begins to undercount the total number of flashes as successive flashes become temporally indistinguishable from each other. This limitation tends to obscure the true functional dependence between f_{NBE} and f_{CG} at these highest rates. However, the linearity seen in the mid-rate region ($f_{CG} / f_{NBE} \sim 10$) probably extends to NBE rates beyond 1 min^{-1} although we cannot verify this in the current study. Another contribution to the flattening at high rates may be a decrease in CG rates that is known to occur at very high total lightning flash rates [*Lang et al*., 2000].

In addition to the data shown in Fig. 2, 115,075 space-time cells with a non-zero f_{CG} were found to have a zero f_{NBE}. However, Fig. 3 shows that these cases seem to be almost exclusively associated with the lowest flash rates (97% of the cases occurred for a $f_{CG} \sim 2$ min^{-1} or less). The implication of Figs. 2 and 3 combined is that elevated CG flash rates (i.e., moderately and strongly convective environments) are almost always accompanied by elevated NBE flash rates.

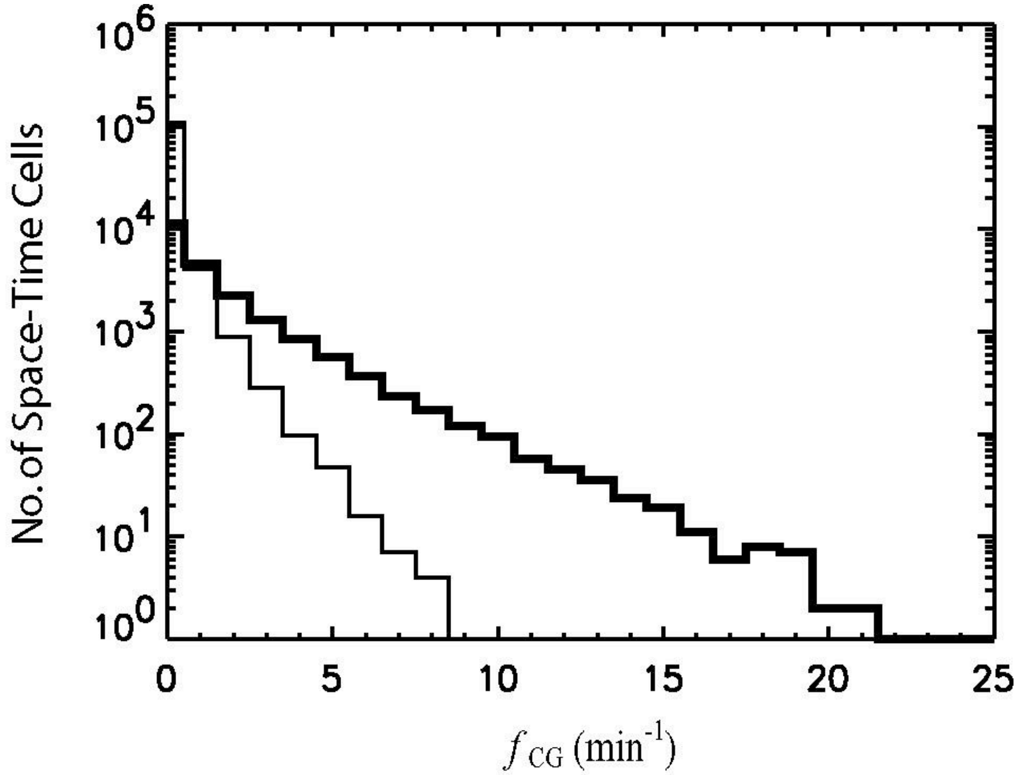

Figure 3. Histogram of LASA CG flash rates, f_{CG}, for all 115,075 space-time cells with zero NBE flash rates (thin line) and the 22,156 cells with non-zero NBE flash rates (thick line).

In summary then, if f_{CG} is assumed to be a proxy for the strength of the convective updraft (and the results of previous studies indicate that, statistically speaking, this is true), the implication of Fig. 2 is that NBE flash rates are statistically correlated to the strength of the associated convective process. This trend appears to be independent of NBE polarity. Results similar to those in Fig. 2 were also obtained by plotting the LASA total lightning flash rate, f_{TOT}, versus

f_{NBE}, although this method has the disadvantage of plotting quantities that are not truly independent of each other.

3.2 NBE Source Heights

LASA NBE waveforms often exhibit a repeating bipolar pattern arising from the original event followed in time by similar but weaker bipolar structures due to one or more reflections off the ionosphere. This phenomenon has been discussed in *Smith et al.* [1999] and is the basis for a geometric technique that uses the inter-pulse time delay and the two-dimensional location of the source event to calculate a source height.

This technique was used to generate Fig. 4a which plots the positive NBE source height, h_{+N}, versus f_{NBE}, for the 52,267 positive NBE events in Fig. 2 for which reflections were present. Each h_{+N} is associated with the f_{NBE} value of the space-time cell within which the NBE event resides. Once again, there is a large variance in the data. However, the low-altitude boundary of the height distribution clearly increases from about 6 km to 12 km with increasing f_{NBE} while the high-altitude boundary decreases only slightly from about 17 km to 15 km. Figure 4b plots the average positive NBE source height, $\langle h_{+N} \rangle$, versus f_{NBE} for the data in Fig. 4a. Again, there is a notable linear increase in $\langle h_{+N} \rangle$ with increasing f_{NBE}. Similar plots of h_{-N} show no dependence on f_{NBE} but are also hampered by poor statistics. The results of Fig. 4 suggest that h_{+N} is statistically correlated to the NBE flash rate, and as a consequence of the results of section 3.1, the strength of convective activity within thunderstorms.

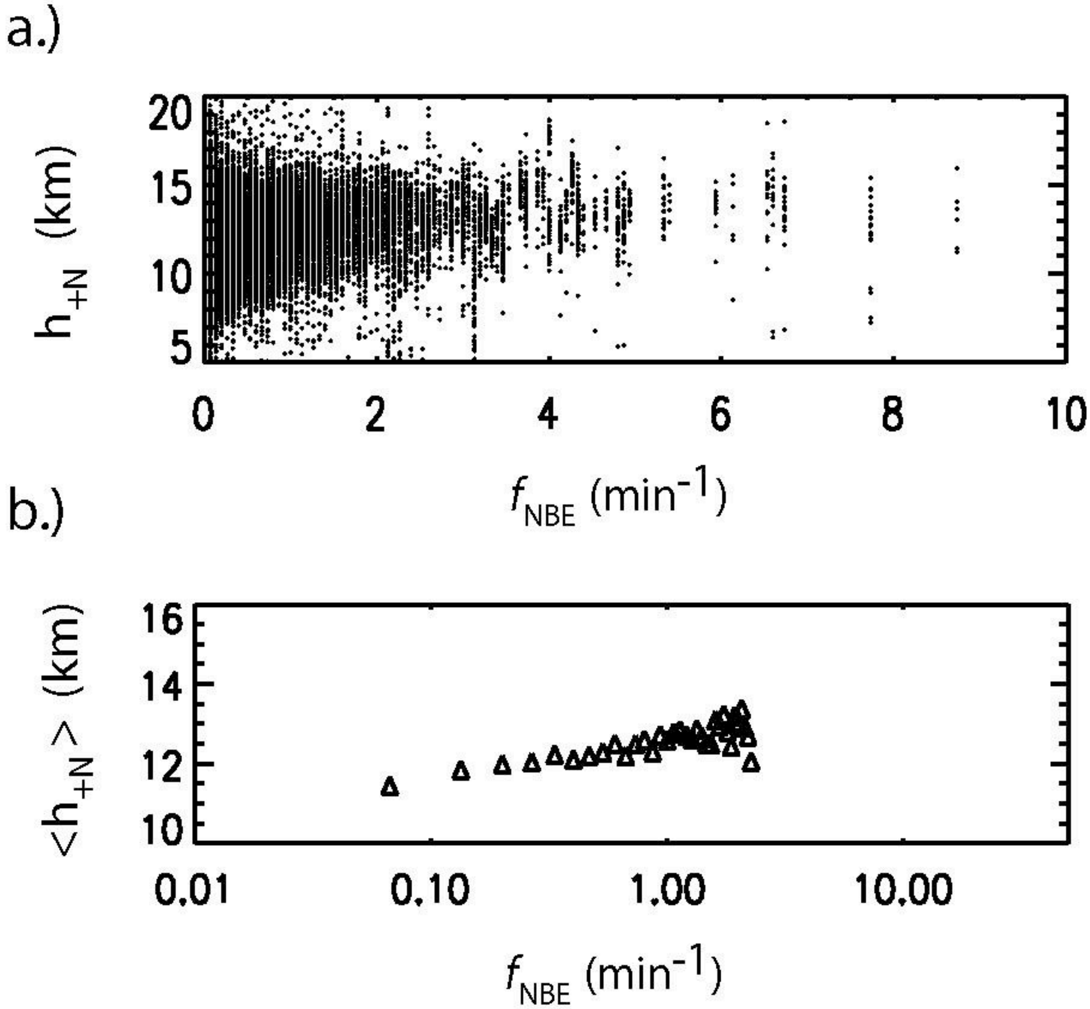

Figure 4. (a.) Positive NBE source height, h_{+N}, versus LASA NBE flash rate, f_{NBE}. (b.) Average positive NBE source height, $\langle h_{+N} \rangle$, versus f_{NBE}.

The results in Fig. 4 are consistent with the ~ 15-km maximum capping height for intense impulsive events observed in the satellite data of *Jacobson* [2003] and with the natural height constraint imposed by the tropopause. They are also consistent with the results described in *Smith et al.* [1999] that suggest a NBE source region in the upper portion of the negative charge layer. However, the 6-km to 17-km altitude span of our data in Fig. 4 further suggests that the NBE source region can lie anywhere between the lower-negative and upper-positive charge regions. The picture that emerges then is that on the average, the charge distributions necessary for NBE production, presumably residing in the volume constrained by the lower-negative charge and upper-positive charge regions in the thundercell, increase in altitude with increasing convective updraft.

4. Future Work

Although the results in sections 3.1 and 3.2 provide a compelling preliminary argument for convection as the primary driver of NBE production, future work must focus on establishing the generality of the results. For example, it is important to compare results as a function of storm type (e.g., severe versus non-severe) and geographical location (e.g., land, ocean, tropical) in order to continue to identify the range of meteorological conditions under which NBE production occurs. Of particular interest is the oceanic/maritime setting where the dynamics of the convective process, the development of the vertical charge distribution, and the composition of the total lightning product differ significantly from that over land. Additional work must focus on individual storm case studies that integrate radar data and meteorological information into the analysis.

A second area of future study is to better quantify the phenomenological differences between the VLF (LASA-detected) characteristics of NBEs and their VHF counterparts that are detected by space-based detectors. Limited correlation studies between the FORTE VHF data set and data from the VLF-based National Lightning Detection Network (NLDN) indicate general similarities between the temporal features in VLF and VHF waveforms. However, a detailed understanding of VLF/VHF differences in the power spectral density and temporal profiles of NBEs will be necessary to predict VHF/NBE detection efficiencies for a given future satellite detection system.

In conclusion, although future satellite-based VHF global lightning monitors will mostly detect signatures of NBE events, the results of this study provide direct evidence that NBE activity is likely a sufficient generic indicator of convective activity and that NBE flash rates and source heights are statistically correlated to the strength of the convective process within a thundercloud.

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